MGO Tutorial - Dewatering Scenario

Introduction

Pumping well optimization technology is used to determine the ideal pumping well locations, and ideal pumping rates at these locations, in order to minimize or maximize a specified criteria. Typically, pumping well optimization is used in the following applications:

- **Groundwater remediation system design**: Pumping well optimization is used to estimate the most cost-effective pump-and-treat groundwater remediation system by minimizing factors such as the number of pumping wells, and total pumping rates, while maintaining capture of the contaminated groundwater plume.
- **Site dewatering system design**: Pumping well optimization is used to estimate the most cost-effective pumping system design by minimizing factors such as the number of pumping wells, and total pumping rates, while maintaining the required water table drawdown.
- **Water Resources Management**: Pumping well optimization is used to estimate the maximum yield of a water supply pumping well, while maintaining a required water level in the aquifer.

These are just a few common examples of the many possible applications for pumping well optimization.

Visual MODFLOW currently supports the public domain version of the Modular Groundwater Optimizer (MGO) program developed by Dr. Chunmiao Zheng and P. Patrick Wang from the University of Alabama, in cooperation with Groundwater Systems Research Ltd. Detailed documentation about the optimization algorithms and capabilities of MGO are provided in the MGO Documentation and User's Guide (Zheng and Wang, 2003). An electronic copy of this document is included on the Visual MODFLOW installation CD-ROM, in the Manual folder.

This tutorial describes how to set up and run a Pumping Well Optimization simulation using Visual MODFLOW. Although some details of the required inputs and parameters will be provided in this chapter, you are encouraged to read the MGO Documentation and User's Guide in order to better understand the benefits and limitations of Pumping Well Optimization using MGO.

NOTE: Some features described in this tutorial are only available in a Pro or Premium version.

Well Optimization Limitations

In Visual MODFLOW, pumping well optimization may only be used under the following conditions:

- **MODFLOW 96** flow engine, with PCG2, SIP, or SOR solver;
- **MT3DMS** transport engine;
- **Steady-State Flow**

Background

This tutorial illustrates a common dewatering scenario in an excavation project. The goal is to lower the water level at a construction site, so that a building foundation can be poured. The goal of the optimization is to minimize the total amount of water pumped, and minimizing the costs, while achieving the head constraints.

Terms and Notations

For the purposes of this tutorial, the following terms and notations will be used:

Type: - type in the given word or value

Select:- click the left mouse button where indicated

⇔ - press the **<Tab>** key

↵ - press the **<Enter>** key

☞ - click the left mouse button where indicated

☞☞ - double-click the left mouse button where indicated

The **bold faced type** indicates menu or window items to click on or values to type in.

[...] - denotes a button to click on, either in a window, or in the side or bottom menu bars.

Opening the Visual MODFLOW Model

Getting Started

On your Windows desktop, you will see an icon for Visual MODFLOW.

☞☞ Visual MODFLOW to start the program

The Dewater model has already been built for you; to open this model,

☞ **File / Open** from the top menu bar.

Browse to the Tutorial/MGO folder, and locate the Dewater.VMF file.

Select this file, and

☞ **[Open]**

You will now briefly examine the Visual MODFLOW model.

☞ **Input** from the top menu bar

This will load the input window of Visual MODFLOW.

As you can see, the model domain is 20 rows by 20 columns, by 5 layers. The X extent is 2000 m; Y extent is 2000m. Total area is ~988 acres.

We will now briefly review the inputs for this model.

☞ **Wells / Pumping Wells** from the top menu bar, to see the well data.

The study area has 16 candidate extraction wells PMP1-PMP16, screened over the bottom two geological layers, and 4 injection wells INJ1-INJ4, screened over layers 3 and 4.

The initial rates of these wells are as follows:

Extraction Wells	**Rate (m3/day)**
PMP1	-100
PMP2	-100
PMP3	-300
PMP4	-500
PMP5	-100
PMP6	-1500
PMP7	-1500
PMP8	-500
PMP9	-100
PMP10	-1500
PMP11	-1500
PMP12	-500
PMP13	-100

Extraction Wells	Rate (m3/day)
PMP14	-100
PMP15	-300
PMP16	-500

The initial rates for the injection wells are as follows:

Injection Wells	Rate (m3/day)
INJ1	100
INJ2	100
INJ3	100
INJ4	100

- ☞ **Properties / Conductivity** from the top menu bar, and then **[Database]** button from the side menu to see the conductivity zones for the model. The default conductivity for this model is 8.64 m/day, and 0.864 m/day vertical conductivity.
- ☞ **Boundaries / General Head** from the top menu bar, and then **Edit>Group** from the side menu to see the boundary conditions for the model. There is a general head of 43 m on the west boundary, and 47 m on the east boundary.
- ☞ **ZBud** from the top menu bar, and then **[Database]** button from the side menu to see the defined zones for the model. The excavation zone is in Layer 3. So, we must switch to the lower layers.
- ☞ **GoTo - Next** button, to change to Layer2
- ☞ **GoTo - Next** button, to change to Layer3

The **Wells** overlay obscures the excavation area zone. To correct this,

- ☞ **[F9-Overlay]** button

In the **Overlay** dialogue deselect BC(F) - Wells overlay.

- ☞ **[OK]**

This model contains two zones.

- Zone 1 (default entire model domain)
- Zone 2 (excavation area). This zone is colored in dark blue.

Zone 2 will contain the head constraints. The goal is to lower the head to 29.5 m, so that the top two layers can be excavated without becoming saturated.

Run Unmananged, Non-optimal Simulation

You will now run the model to see the results of the dewatering, using the current pumping rates, without optimization.

- ☞ **File / Main Menu** from the top menu bar
- ☞ **Run** from the top menu bar
- ☞ **Run** from the main menu bar, a second time.
- ☞ **Translate & Run**

The MODFLOW 96 numeric engines will then run. This should take approximately 30 seconds, depending on system resources.

When this is complete,

- ☞ **Close** button.

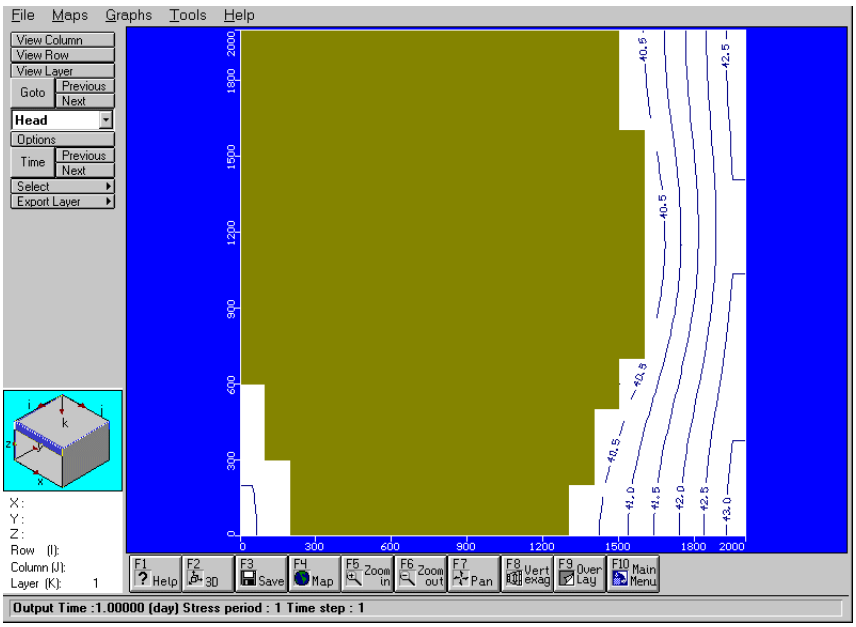
Then, to see the output,

- ☞ **Output** from the main menu bar.
- ☞ **[GoTo]**

Type: 1

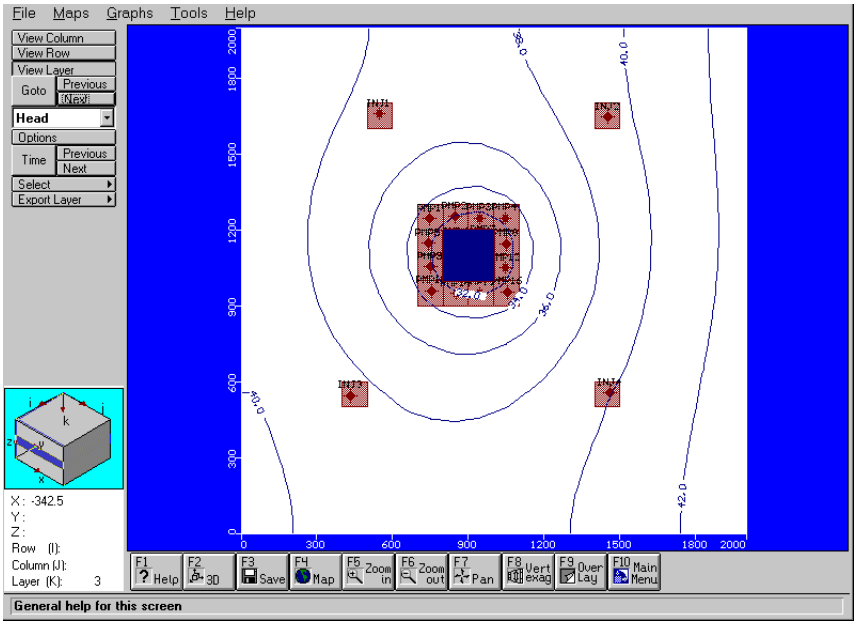
- ☞ **[F9-Overlay]**
- ☞ Check the box beside C(I) - Contour labels

The output window will appear similar to the figure shown below.



The olive colored cells represent dry cells in the upper layer. The upper layer is nearly completely dry, due to intensive pumping. Next, we need to move to layer 3, which contains the zone for the head constraints.

- ☞ **GoTo - Next** button, to change to Layer2
- ☞ **GoTo - Next** button, to change to Layer3, and you should see the contoured heads as shown below.



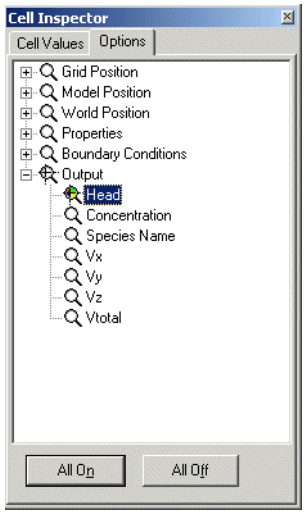
For this example, we are mainly interested in the calculated heads in the excavation location. Therefore, we can turn off the unnecessary output overlays.

- ☞ **[F9-Overlay]**
- ☞ Deselect all overlays except Heads, Zone Budget, Dry Cells, and Pumping Wells.
- ☞ **[OK]**

You may display the exact cell-by-cell values using the **Cell Inspector**, if you wish.

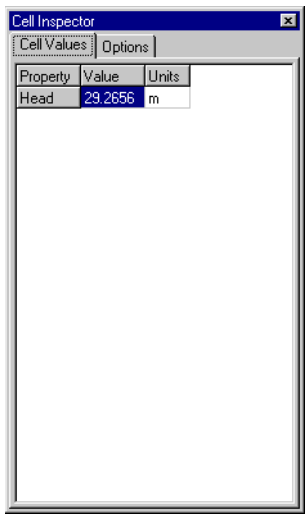
To do so,

- ☞ **Tools / Cell Inspector** from the main menu
- ☞ **Options** tab



- ☞ Under **Output**, turn on Head
- ☞ **Cell Values** tab

Then, move your mouse cursor over the excavation zone (Zone2, colored dark blue) to see the exact calculated head values.



As you will recall, that the head must be < 29.5 for the excavation area. You will see the maximum value is ~29-30 m for this model. So, the current pumping rates satisfy our conditions. However, in this scenario, there are likely too many pumping wells operating (16), resulting in too much water being extracted from the system, which can become very costly.

You will now use MGO to optimize this scenario. MGO will help determine a pumping strategy that is needed to reach these head constraints and minimize costs; this includes an optimal pumping rate, and an optimal number of pumping wells that should be installed.

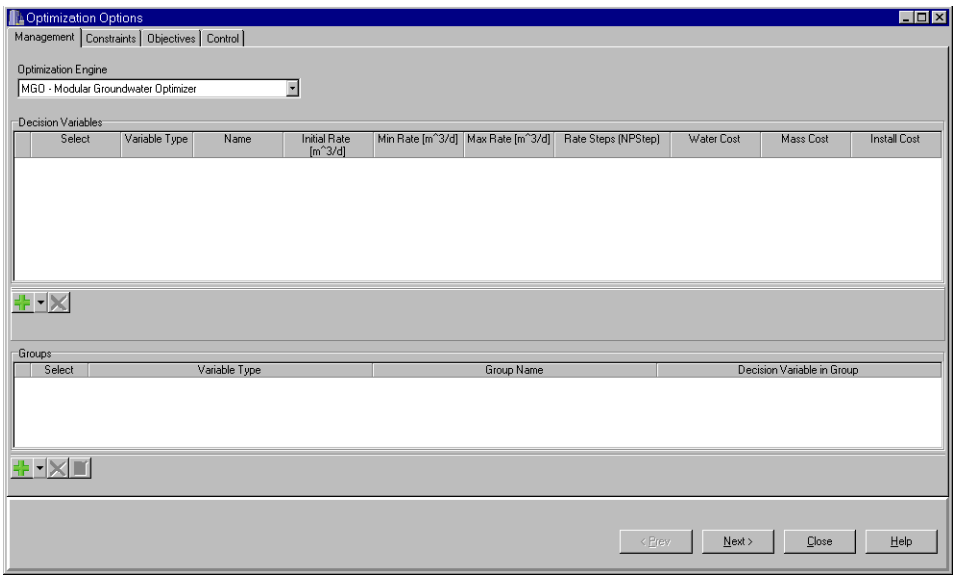
We will now proceed to define the MGO optimization settings.

Defining MGO Input

To load the MGO input module,

- ☞ **File / Main Menu** from the top menu bar
- ☞ **Run** from the top menu bar
- ☞ **Optimization / Well Optimization** from the main menu.

This will load the Optimization Options window as shown below.



- ☞ **MGO** for the Optimization engine.

You will now define the decision variables for the dewatering problem.

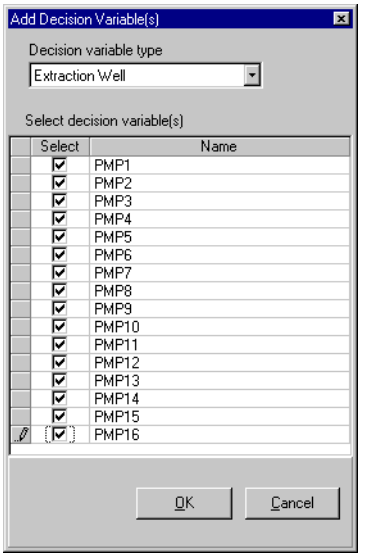
Defining MGO Decision Variables and Groups

A **Decision Variable** (DV) is a model input that may be influenced or controlled by the user. These are the inputs that you are trying to optimize. For MGO, the DVs are limited to Pumping Wells (Extraction and/or Injection Wells).

Adding Decision Variables

In this exercise, you will add all the candidate extraction wells as decision variables.

- the **Add Decision Variable** button located below the table, and the following **Add Decision Variable(s)** window will appear:



This window lists all of the **Extraction Wells** and/or **Injection Wells** in the model.

- **Extraction Well** at the top
- Select all the wells from the list
- **[OK]** to close the dialog

For each decision variable, enter the following **Min Rate**.

type: **0** m3/day

For each decision variable, enter the following **Max Rate**

type: **5000** m3/day

Note: In the Well Optimization packages, pumping rates are treated as absolute values. It is not necessary to define extraction rates as negative values, or injection rates as positive values.

For each decision variable, enter the following **Water Cost**.

type: **0.25**

For each decision variable, enter the following **Mass Cost**.

type: **1**

For each decision variable, enter the following **Install Cost**.

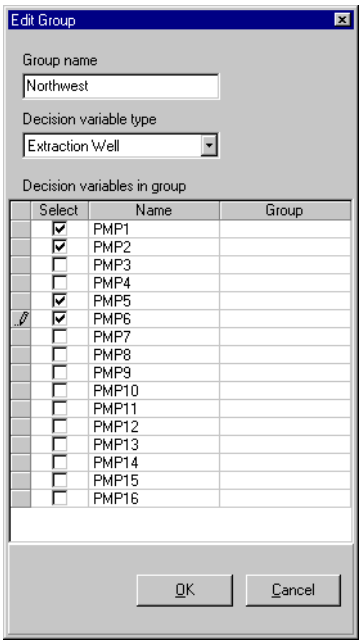
type: **5000**

Defining Decision Variable Groups

A Decision Variable Group (DV Group) is a collection of individual DVs which may have similar 'interests'. These DV Groups are used for different purposes depending on which optimization engine is selected. When using MGO, a DV Group may only be used to define pumping balance constraints. A DV Group must contain a minimum of one active DV.

For this example, you group the extraction wells into their location on the dewatering site. To create a new DV Group,

☞ the **Add Decision Variable Group** button located below the table, and the following **Edit Group** window will appear:



Type: Northwest at the top, for the name

- ☞ **Extraction Well** for the type
- ☞ **PMP1, PMP2, PMP5, PMP6**
- ☞ **[OK]** to close the dialog. The new DV Groups will appear in the table.

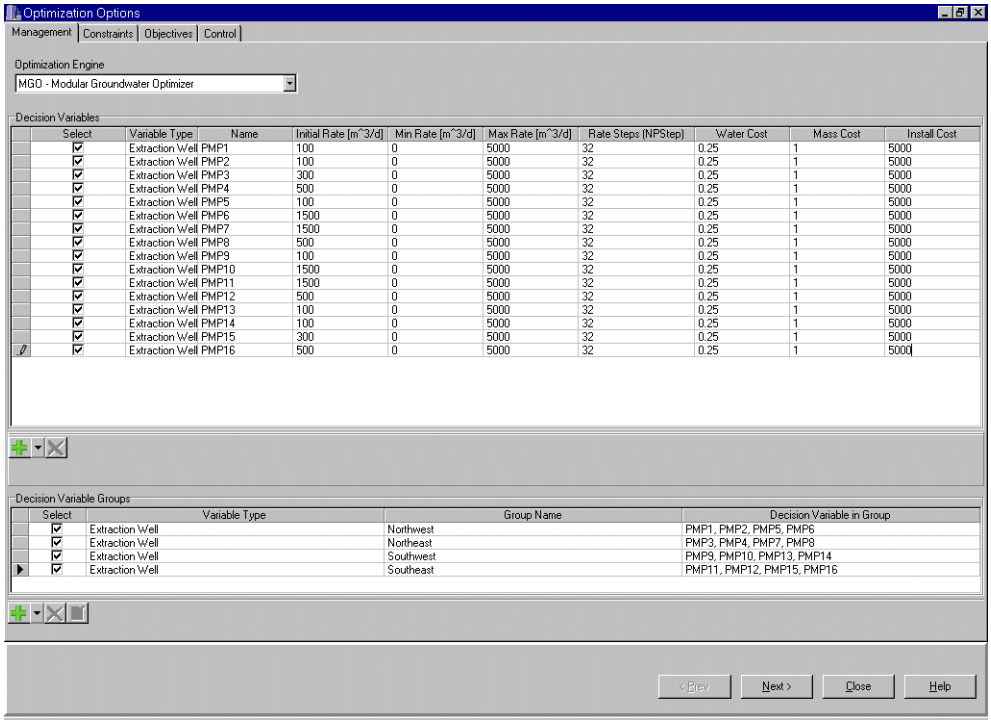
You will now create three more groups, using the same procedure.

Create a group called Northeast, and add wells: **PMP3, PMP4, PMP7, PMP8**

Create a group called Southwest, and add wells: **PMP9, PMP10, PMP13, PMP14**

Create a group called Southeast, and add wells: **PMP11, PMP12, PMP15, PMP16**

This concludes the requirements for Decision variables. If you have entered the data successfully, your window should be similar to the figure shown below.


Optimization Options
Management
Constraints
Objectives
Control
Optimization Engine
MGO - Modular Groundwater Optimizer
Decision Variables
Select
Variable Type
Name
Initial Rate [m^3/d]
Min Rate [m^3/d]
Max Rate [m^3/d]
Rate Steps (NPStep)
Water Cost
Mass Cost
Install Cost
Extraction Well PMP1 100 0 5000 32 0.25 1 5000
Extraction Well PMP2 100 0 5000 32 0.25 1 5000
Extraction Well PMP3 300 0 5000 32 0.25 1 5000
Extraction Well PMP4 500 0 5000 32 0.25 1 5000
Extraction Well PMP5 100 0 5000 32 0.25 1 5000
Extraction Well PMP6 1500 0 5000 32 0.25 1 5000
Extraction Well PMP7 1500 0 5000 32 0.25 1 5000
Extraction Well PMP8 500 0 5000 32 0.25 1 5000
Extraction Well PMP9 100 0 5000 32 0.25 1 5000
Extraction Well PMP10 1500 0 5000 32 0.25 1 5000
Extraction Well PMP11 1500 0 5000 32 0.25 1 5000
Extraction Well PMP12 500 0 5000 32 0.25 1 5000
Extraction Well PMP13 100 0 5000 32 0.25 1 5000
Extraction Well PMP14 100 0 5000 32 0.25 1 5000
Extraction Well PMP15 300 0 5000 32 0.25 1 5000
Extraction Well PMP16 500 0 5000 32 0.25 1 5000
Decision Variable Groups
Select
Variable Type
Group Name
Decision Variable in Group
Extraction Well Northwest PMP1, PMP2, PMP5, PMP6
Extraction Well Northeast PMP3, PMP4, PMP7, PMP8
Extraction Well Southwest PMP9, PMP10, PMP13, PMP14
Extraction Well Southeast PMP11, PMP12, PMP15, PMP16
< Prev
Next >
Close
Help

☞ **[Next]** to proceed to the next window

Defining Constraints

The management objectives must be achieved within a set of constraints, which may be derived from technical, economic, legal, or political conditions associated with the project. There may be constraints on decision variables and state variables, and they may take the form of either equalities or inequalities. Constraints on the decision variables include the number of candidate wells, the upper and lower bounds for pumping/injection rates, and the candidate well locations. Constraints on the state variables might include the requirement that hydraulic heads be maintained above or below a certain level, or that contaminant concentrations not exceed regulatory standards at specified compliance points (Zheng and Wang, 2003).

In this example we will define constraints on the pumping rates and on the head values for the pumping well screens.

Global Constraints

The Global Constraints are applied to all Decision Variables as a whole, and influence the total pumping rate and the total number of active pumping wells.

Under the **Global Constraints**, define the following options:

☞ **Yes** to **Use Global Rate Constraint**

type: **-10,000** for the **Minimum Total Pumping Rate** value

type: **0** for the **Maximum Total Pumping Rate**

☞ **Specify number of active wells** for the **Well Location Optimization**.

type: **4** for the **Max active wells**

type: **500,000** for the **Max active penalty**

Pumping Balance Constraints

The **Pumping Balance Constraints** establish the dependence relationships among different wells. They are imposed to link the flow rates of unmanaged wells with those of managed wells. This option is only available for the MGO engine.

In this scenario, we want to specify that: Total Injection = Total Extraction.

We force the total sum of extraction rates to equal the total injection rate because all water obtained from extraction wells will be reinjected into the ground. This is often important for water supply, environmental, and economic reasons.

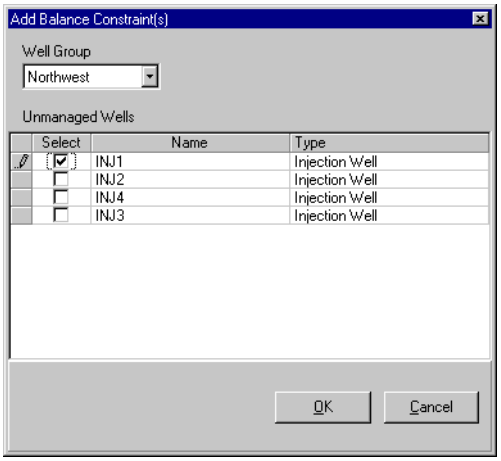
In MGO, Injection wells will be added in the constraints as unmananged wells. (Unmanaged wells are pumping blocks whose rate is fixed in the input, and are not used as a decision variable or computed in the MGO simulation.)

We will add the four injection wells, in order to balance out the flow of the four extraction wells. Each injection well will have a -1.0 multiplication factor, to balance the rates We will assign one injection well to each group of extraction wells.

In order to specify a **Balance Constraint** for MGO using Visual MODFLOW, the unmanaged wells must already be present in the model, and the managed pumping wells may only be selected if they belong to a DV Group. You will recall that we have already added this DV group in the Management tab.

To add a new **Balance Constraint**,

☞ **Add Balance Constraint** button located below the table. The following **Add Balance Constraint(s)** window will appear:



- **Northwest** group at the top

Next, you must select one unmanaged injection well.

- **INJ1**
- **[OK]** to close the dialog

Repeat this step for the other injection wells:

- **Add Balance Constraint** button located below the table.
- **Northeast** group at the top
- **INJ2**
- **[OK]** to close the dialog

- **Add Balance Constraint** button located below the table.
- **Southwest** group at the top
- **INJ3**
- **[OK]** to close the dialog

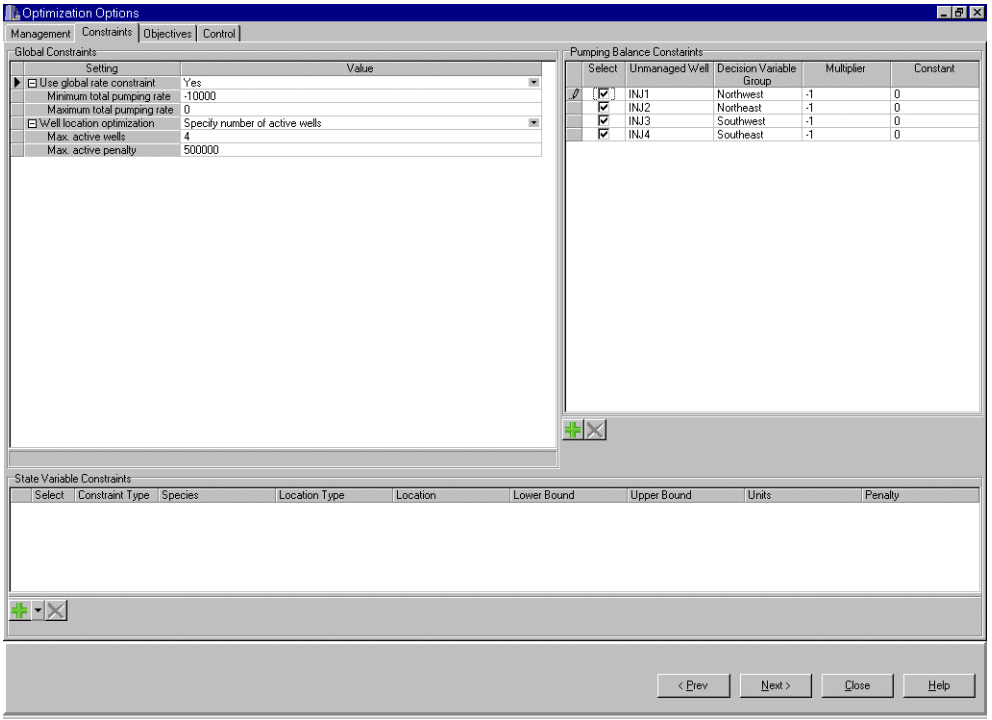
- **Add Balance Constraint** button located below the table.
- **Southeast** group at the top
- **INJ4**
- **[OK]** to close the dialog

Next, you must specify the multiplier and constant for the injection wells

type: **-1** for the **Multiplier** for each well

type: **0** for the **Constant** for each well

When you are done, the Constraints should be similar to the image shown below.



State Variable Constraints

The **State Variable Constraints** are constraints based on system responses to the stresses introduced by the Decision Variables. These typically include constraints such as minimum and maximum allowed values of head, or concentration, at a selected location.

For this simulation, we will add the Head constraint, which is the water elevation we are trying to achieve, in order to do the excavation.

- **Add State Variable** button located below the grid.

In the Add State Variables Dialog,

- **Head** under **State Variable Type**

☞ **Zone2** (which contains the excavation zone)

☞ **[OK]**

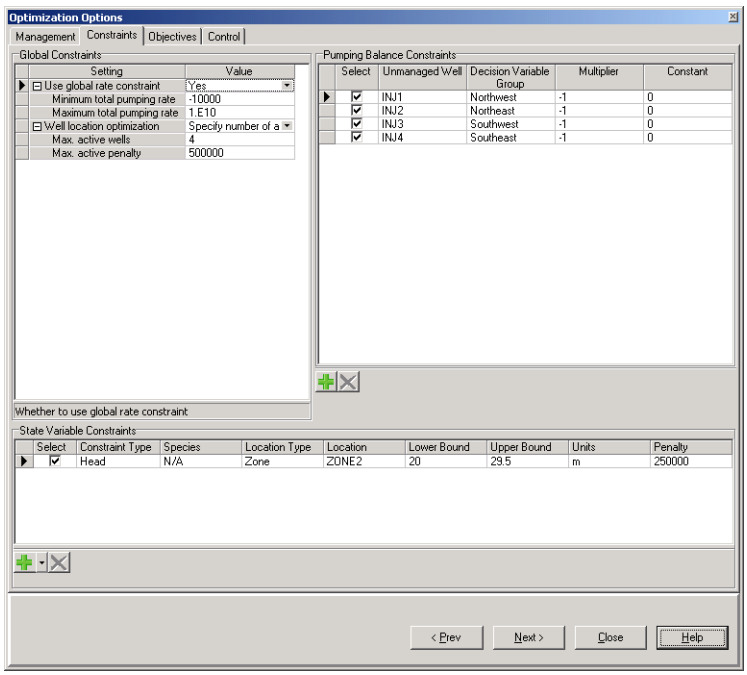
In the State Variables Constraints grid, define the bounds for the constraints:

type: **20** (m) for the **Lower Bound**

type: **29.5** (m) for the **Upper Bound**

type: **250,000** for the **Penalty** value

Once you are finished, the Constraints window should be similar to the one shown below.



☞ **[Next]** to proceed to the next window.

Defining Optimization Objectives

The objectives for an optimization problem can be defined as the net present value of the management costs, taken over an engineering planning horizon. The costs can include the capital costs associated with well drilling and installation, and operation costs associated with pumping and/or treatment over the lifetime of the project. Other forms of the objective function are also possible. For example, for a long-term contamination containment system, the objective function can be defined simply in

terms of the total pumping volume, since the one-time drilling and installation costs may be negligible compared to the cumulative pumping and treatment costs. The exact form of the objective function depends on the nature of each individual problem.

In this window, define the optimization options:

- ☞ **Minimize** for the Objective Direction.

For Scenario 1, you will use the Objective:

- ☞ **System Installation Cost**
- ☞ **Total Water Extracted**
- ☞ Deselect the other objectives

For this objective, the default min and max values are sufficient.

- ☞ **[Next]** to proceed to the next window

Defining Control Options

The **Control Options** define the settings that control the numerical aspects of the optimization process. These settings are used to 'tune' the optimization process.

Solver Settings

MGO supports three different solvers for the Optimization process:

- Genetic Algorithm (GA)
- Simulated Annealing (SA)
- Tabu Search (TS)

- ☞ **Genetic Algorithm** for the **Solver**

For this simulation, the default Solver settings are fine.

Solution Settings

The default solution settings are sufficient for this simulation.

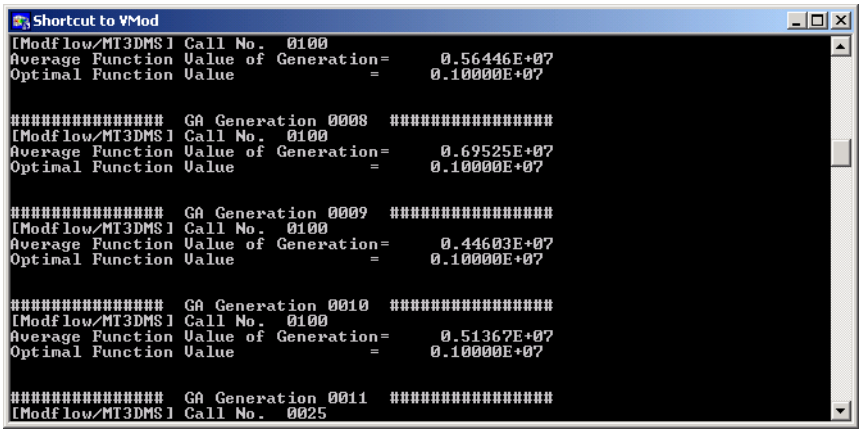
Output Settings

The default output settings are sufficient for this simulation.

- ☞ **[Run]** to begin the simulation

Running Simulation and Viewing Output

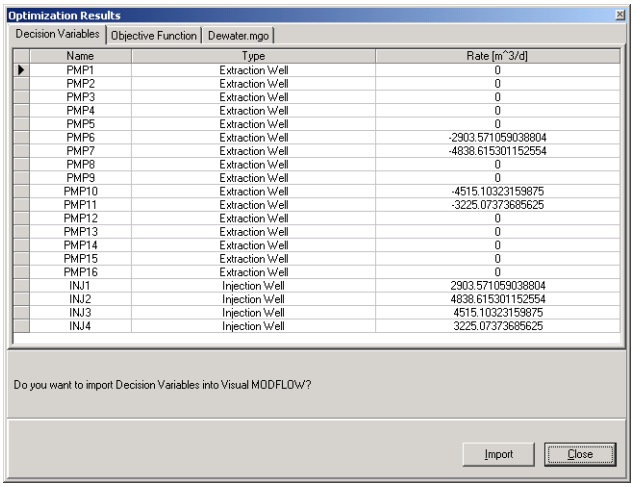
When you click Run, this will launch the MGO engine, automatically translate the Visual MODFLOW and MGO input files, and launch the necessary numeric engines. The MGO engine will run in a DOS window, as shown in the following figure:


Shortcut to VMod
[Modflow/MT3DMS] Call No. 0100
Average Function Value of Generation= 0.56446E+07
Optimal Function Value = 0.10000E+07
################ GA Generation 0008 ################
[Modflow/MT3DMS] Call No. 0100
Average Function Value of Generation= 0.69525E+07
Optimal Function Value = 0.10000E+07
################ GA Generation 0009 ################
[Modflow/MT3DMS] Call No. 0100
Average Function Value of Generation= 0.44603E+07
Optimal Function Value = 0.10000E+07
################ GA Generation 0010 ################
[Modflow/MT3DMS] Call No. 0100
Average Function Value of Generation= 0.51367E+07
Optimal Function Value = 0.10000E+07
################ GA Generation 0011 ################
[Modflow/MT3DMS] Call No. 0025

Once the optimization simulation is complete, the DOS window will close automatically, and an **Optimization Results** window will open. Interpreting the results is explained in the following section.

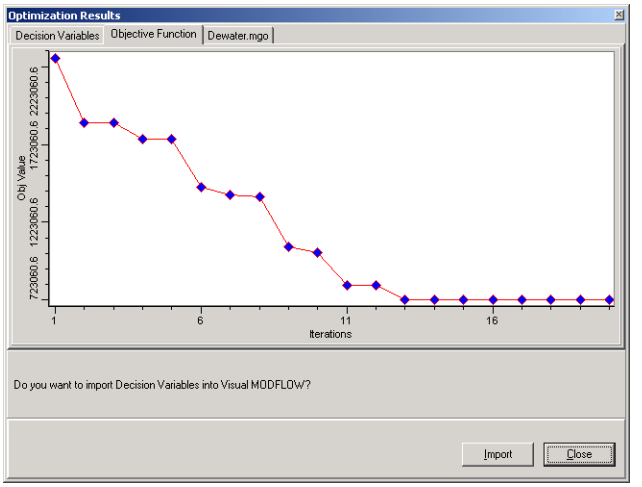
Interpreting and Utilizing Well Optimization Results

Once the simulation is complete, the **Optimization Results** window (as shown in the following figure) will appear:

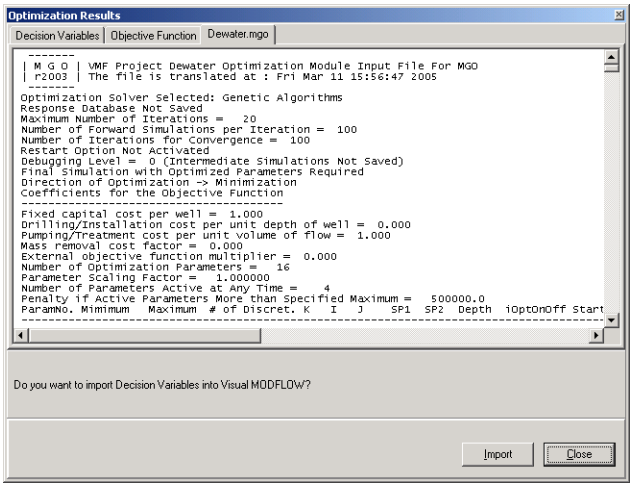


The GA solver uses Heuristic algorithms in an attempt to find the optimal solution. Consequently, your results may vary, but they should be similar.

In the **Decision Variables** tab, we can see that MGO calculated an optimal extraction rate for three or four extraction wells. It also calculated an equal injection rate for three or four injection wells, such that the constraint that injection = extraction is satisfied. In addition, the global constraint of 10,000 m3/day for maximum pumping rate was not exceeded.



In the **Objective Function** tab, we can see progress of the calculated objective function value through the course of the simulation, at each iteration. You will recall, for this simulation, we used 20 iterations.


Optimization Results
Decision Variables
Objective Function
Dewater.mgo
| M G O | VMF Project Dewater Optimization Module Input File For MGO
| r2003 | The file is translated at : Fri Mar 11 15:56:47 2005
Optimization Solver Selected: Genetic Algorithms
Response Database Not Saved
Maximum Number of Iterations = 20
Number of Forward Simulations per Iteration = 100
Number of Iterations for Convergence = 100
Restart Option Not Activated
Debugging Level = 0 (Intermediate Simulations Not Saved)
Final Simulation with Optimized Parameters Required
Direction of Optimization -> Minimization
Coefficients for the Objective Function
Fixed capital cost per well = 1.000
Drilling/Installation cost per unit depth of well = 0.000
Pumping/Treatment cost per unit volume of flow = 1.000
Mass removal cost factor = 0.000
External objective function multiplier = 0.000
Number of Optimization Parameters = 16
Parameter Scaling Factor = 1.000000
Number of Parameters Active at Any Time = 4
Penalty if Active Parameters More than Specified Maximum = 500000.0
ParamNo. Mimimum Maximum # of Discret. K I J SP1 SP2 Depth iOptOnOff Start
Do you want to import Decision Variables into Visual MODFLOW?
Import
Close

Finally, the **MGO Output file (.MGO)** displays the MGO simulation input file and output file.

Now, we need to confirm that these optimized injection/extraction rates have satisfied the constraints we have defined. To do so, we must view the Visual MODFLOW results.

Since we do not want to overwrite the original pumping rates with these calculated pumping rates, we will not import the MGO results into Visual MODFLOW.

☞ **[Close]** button.

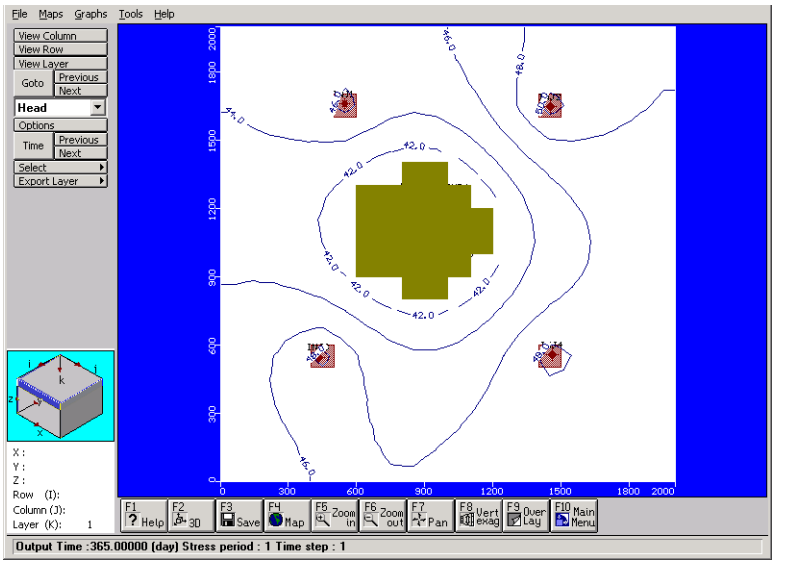
Next, we will load the output of Visual MODFLOW. Please continue in the next section.

Viewing Visual MODFLOW Output

To load the Visual MODFLOW output,

☞ **Output** from the main menu bar

The Visual MODFLOW output window will load



In the output, you will see olive-colored cells, which represent dry cells.

First, we must switch to the lower layers

☞ **GoTo - Next** button, to change to Layer2

☞ **GoTo - Next** button, to change to Layer3

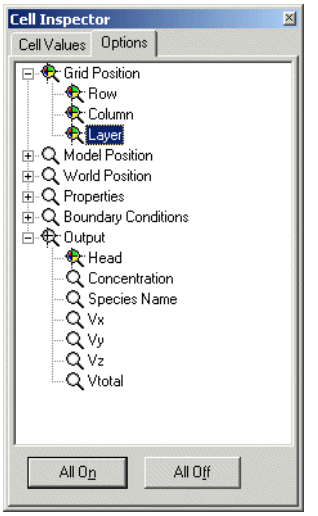
For this example, we are mainly interested in the calculated heads in the excavation location. Therefore, we can turn off the unnecessary output overlays.

- **F9** button.
- Turn on Heads, Zone Budget, Dry Cells, and Pumping Wells.
- Deselect all other overlays
- **[OK]**

You may display the exact cell-by-cell values, using the Cell Inspector, if you wish.

To do so,

- **Tools / Cell Inspector** from the main menu
- **Options** tab

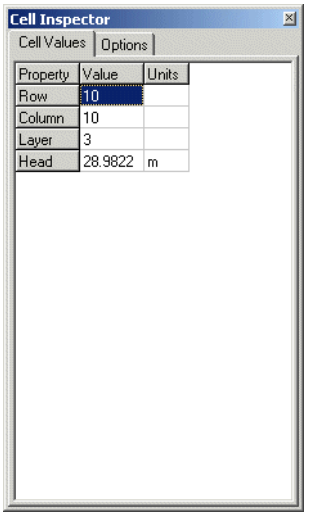


Under **Grid Position**, turn on Row, Column, Layer

Then, under **Output**, turn on Head

- **Cell Values** tab

Then, move your mouse cursor over the excavation zone to see the exact calculated head values. You will recall, that the head must be < 29.5 m in order to dewater the excavation site. You will see the calculated head values in the excavation zone is ~29-30 m.



Therefore, we can conclude that the pumping rates calculated by MGO have satisfied our head constraints. We can then consider these well locations and pumping rates as a potential dewatering scenario for this site.

References

Utah State University and Peralta and Associates Inc, 2003. *SOMOS: Simulation/ Optimization Modeling System. Optimization Software for Managing Groundwater Flow, Solute Transport, and Conjunctive Use. User's Manual for Lite and Standard Versions.*

Zheng, C. and Wang, P., 2003: *MGO Modular Groundwater Optimizer Incorporating MODFLOW/MT3DMS: Documentation and User's Guide.* The University of Alabama, in cooperation with Groundwater Systems Research Ltd.